May I Ask You Where You Have Been, Photon?

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PH4040 Advanced Skills

Outline

1. Background
   - Motivation
   - Mach-Zehnder interferometer
   - Quantum mechanics
2. Asking Photons Where They Have Been
   - Danan et al. experiment
   - Phantom photons

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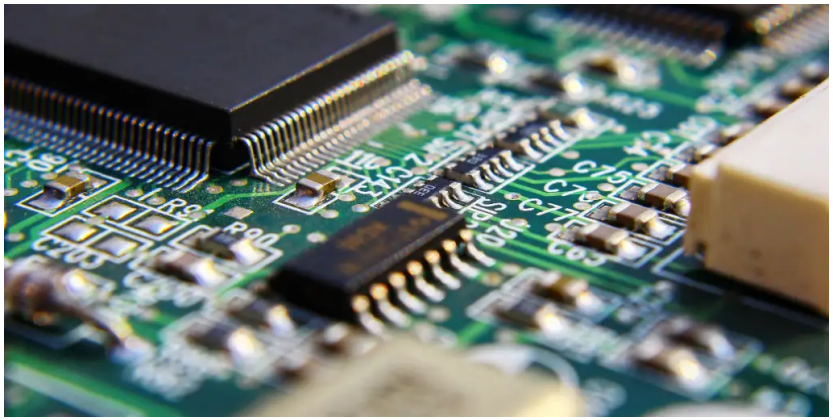
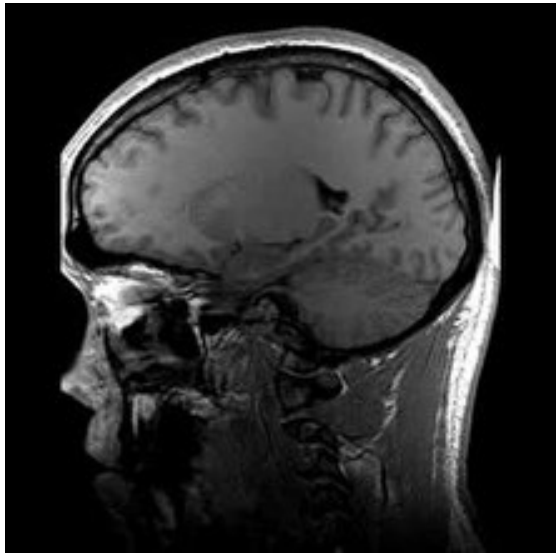
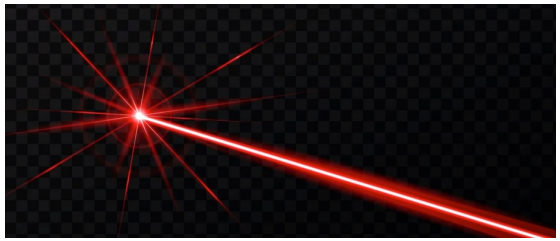
Quantum technology

- Silicon chips
- Lasers
- Superconductors
- Everything!







Quantum questions

Some things we still don't agree on:

- What is an "observer"?
- How does a wave function know to collapse?
- Is measurement an irreversible phenomenon, vs time-symmetric evolution of wave-functions?

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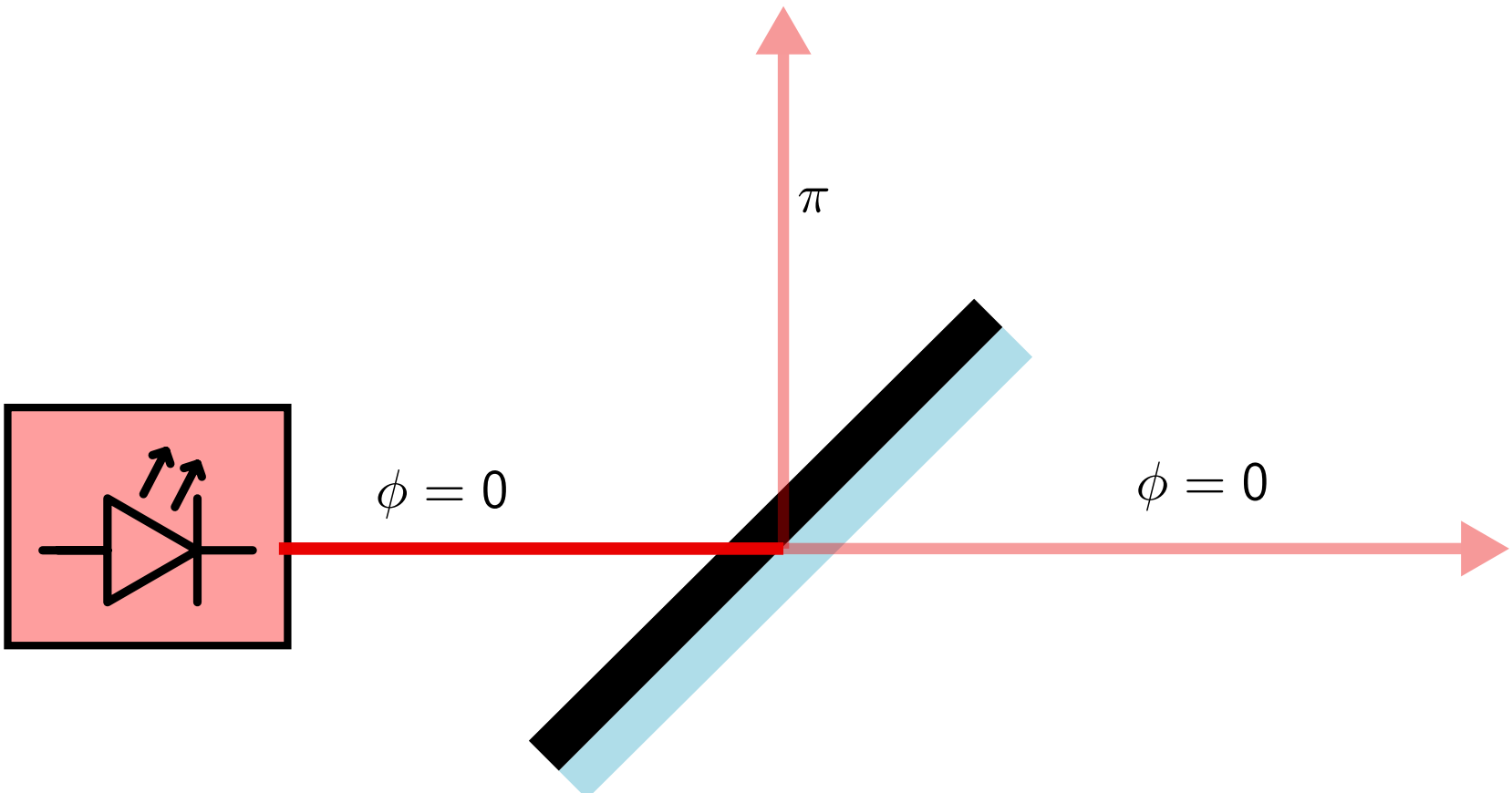
Beam splitter

- Splits beam into two perpendicular arms of $\frac{1}{2}$ intensity
- Light reflected by silvered side phase shifted by π



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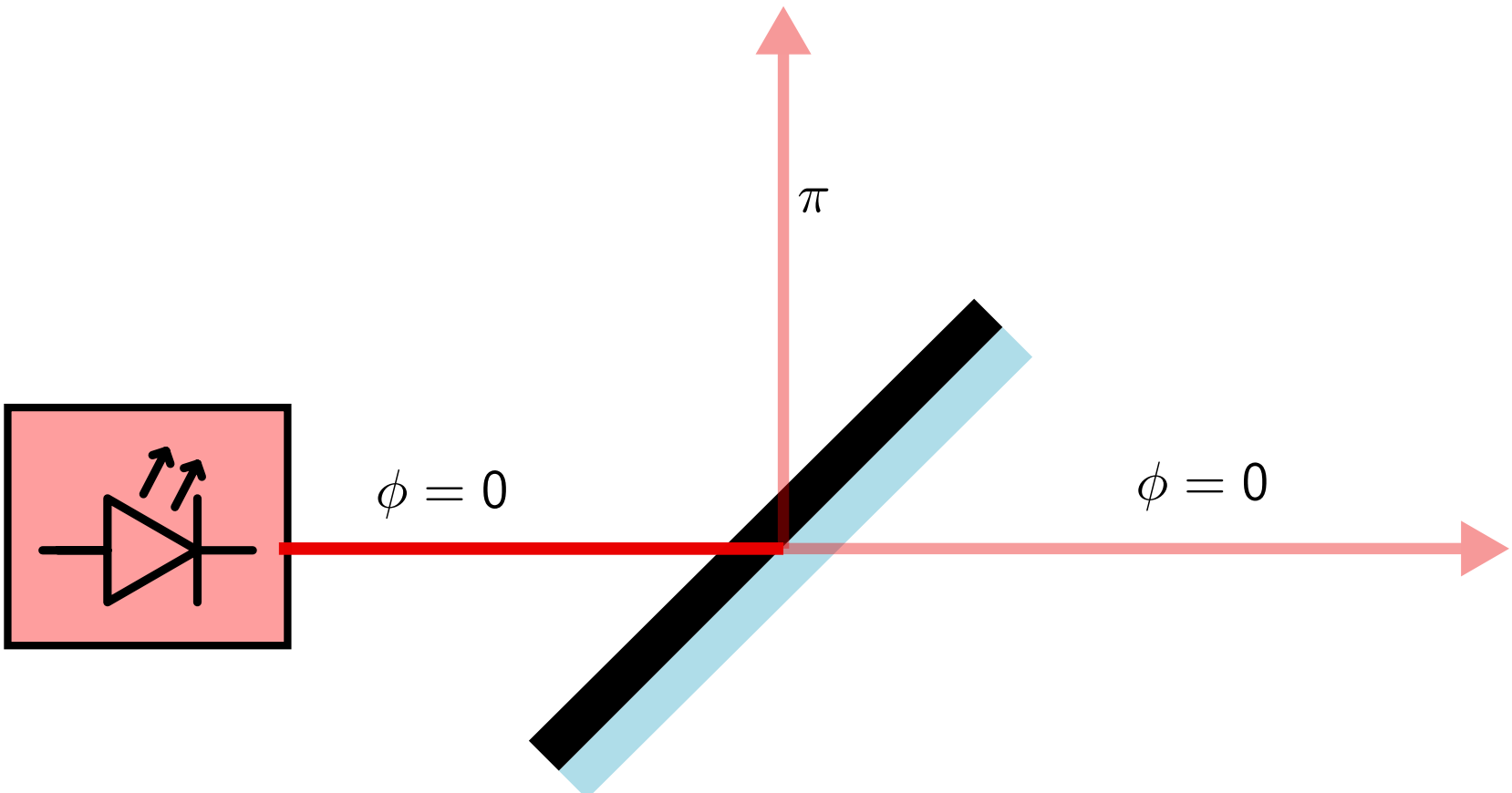
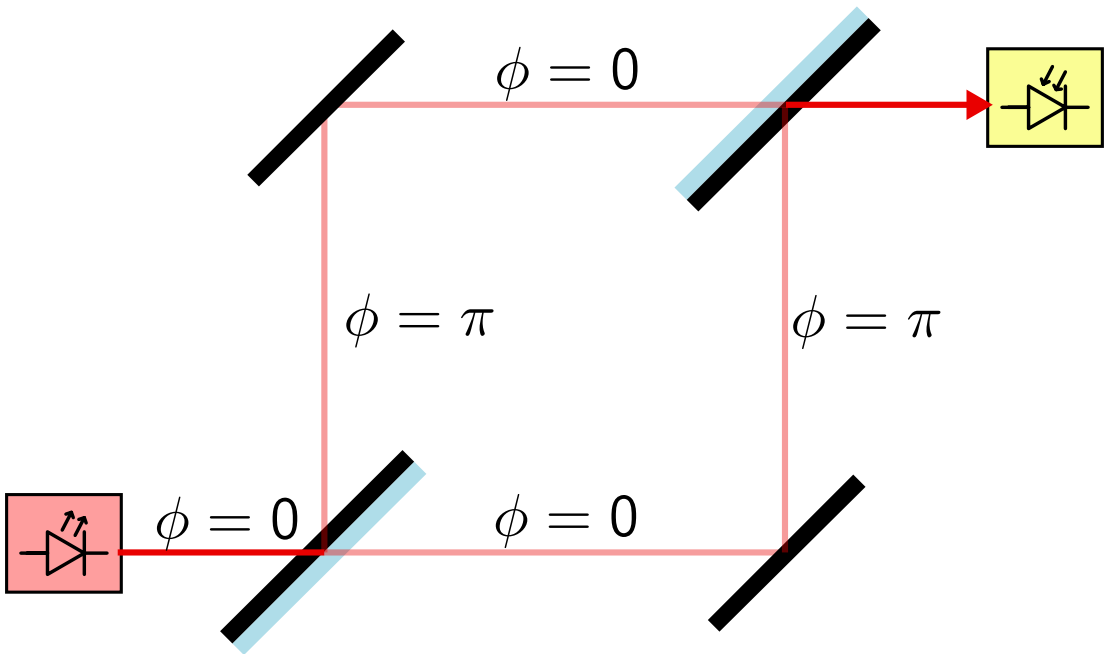


Mach-Zehnder interferometer

- Constructive interference between beams of the same phase
- Destructive interference between beams of opposite phase



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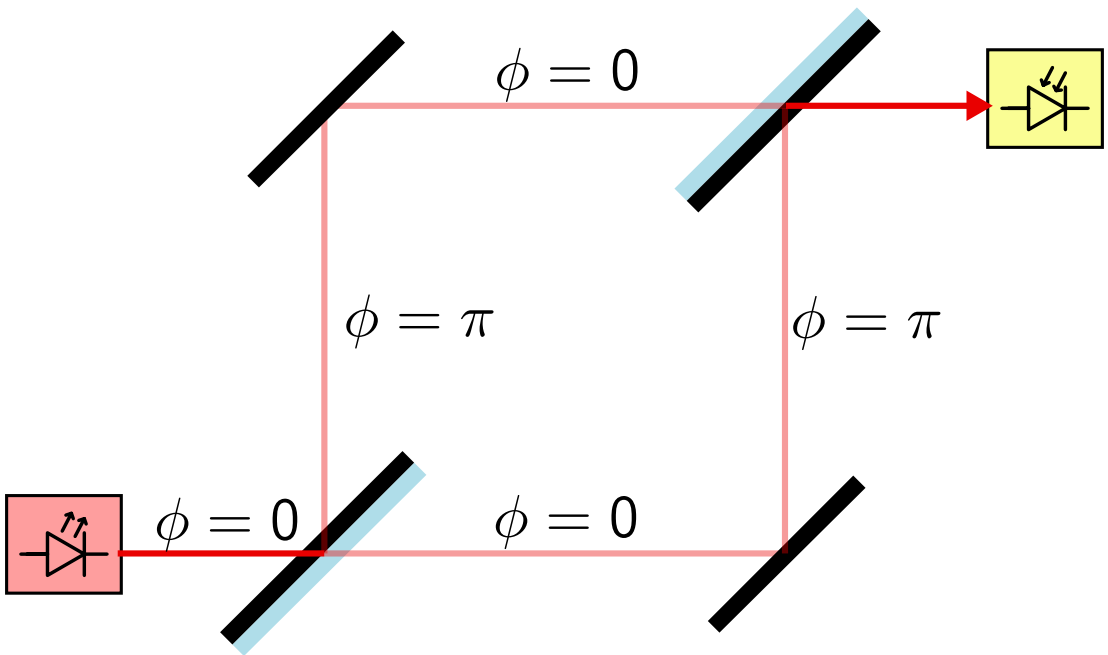

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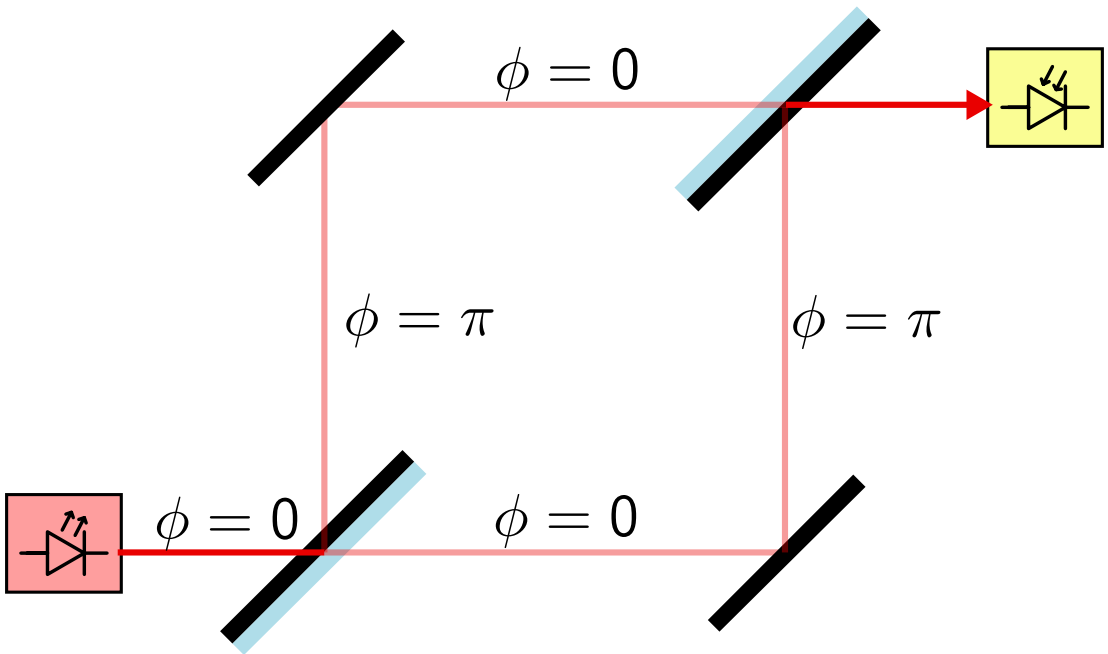
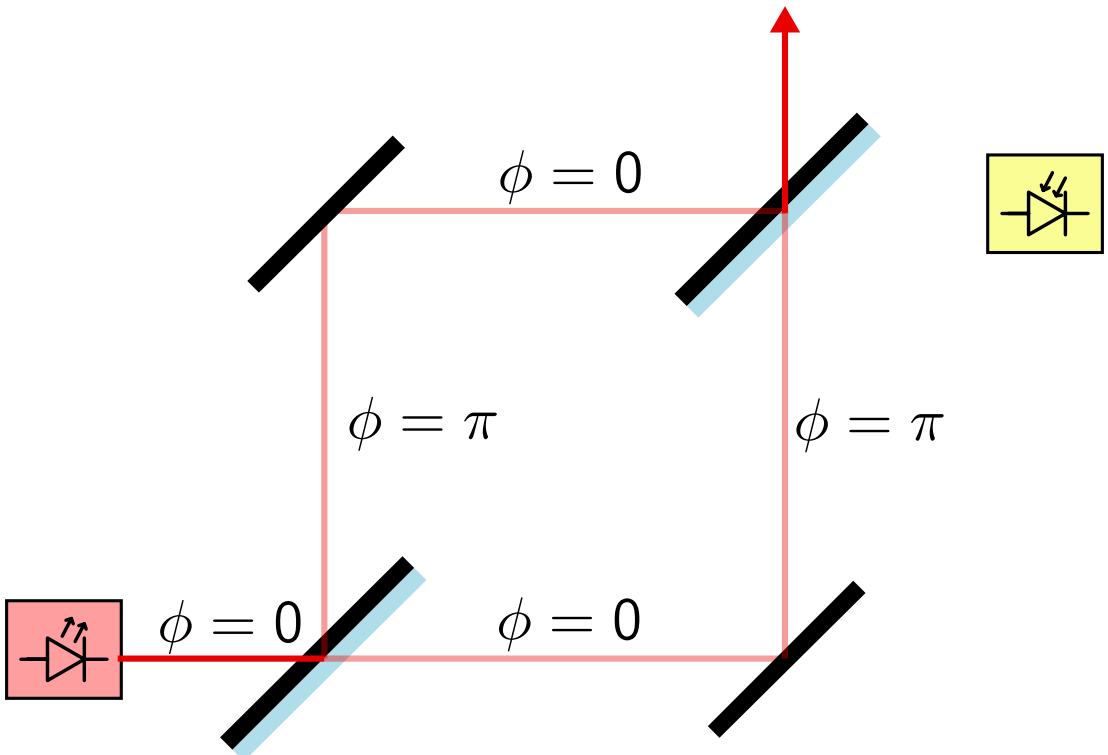


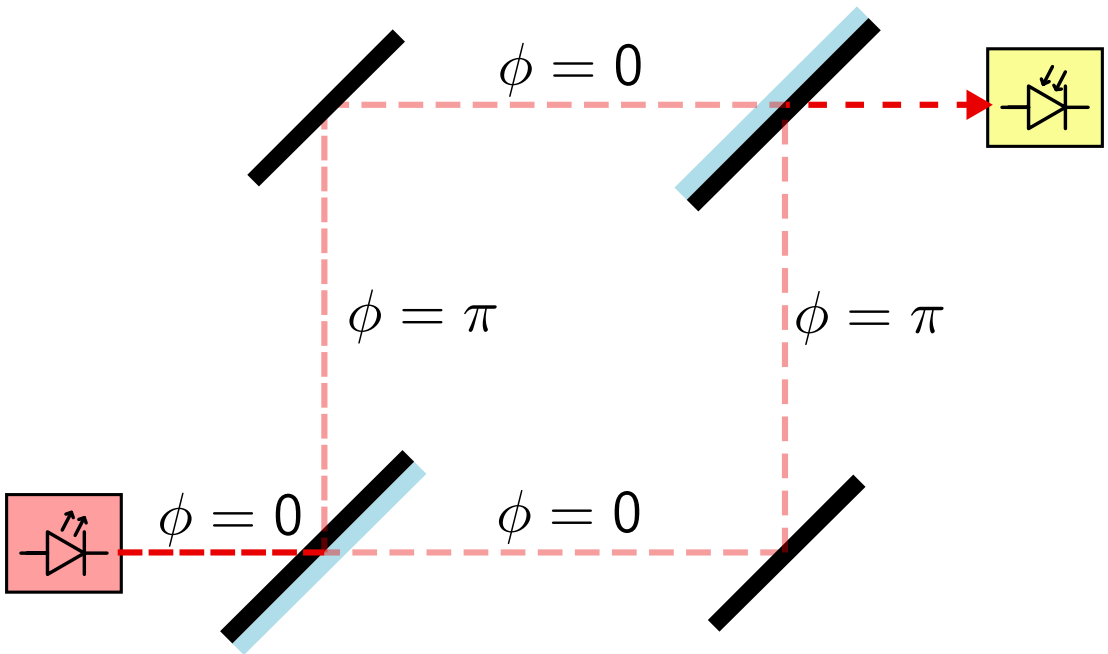
Mach-Zehnder interferometer

Flipping the second beam splitter changes the final direction of the beam



Single photon interference

- Example of wave-particle duality
- Similar to double slit experiment



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Bra-ket notation

- Quantum states are represented by (unit) state vectors, written $|\psi\rangle$
- Dual space containing $\langle\psi|$.
- Arithmetic:
  - $\langle\psi|\psi\rangle = 1$
  - $|\langle A|B\rangle|^2$ gives probability of $|A\rangle$ given $|B\rangle$
  - etc.

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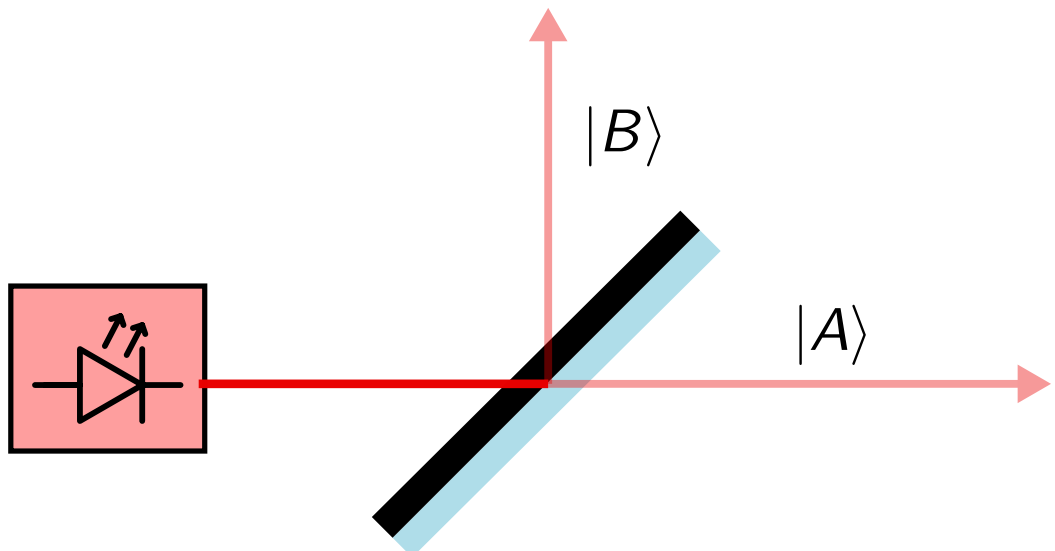
Bra-ket notation

- Photon's state after encountering beam splitter is given by $|\psi\rangle = \frac{1}{\sqrt{2}}|A\rangle + \frac{1}{\sqrt{2}}|B\rangle$
- Likelihood of transmission given state $|\psi\rangle$:

$$|\langle A|\psi\rangle|^2 = \left|\langle A|\left(\frac{1}{\sqrt{2}}|A\rangle + \frac{1}{\sqrt{2}}|B\rangle\right)\right|^2 = \frac{1}{2}$$



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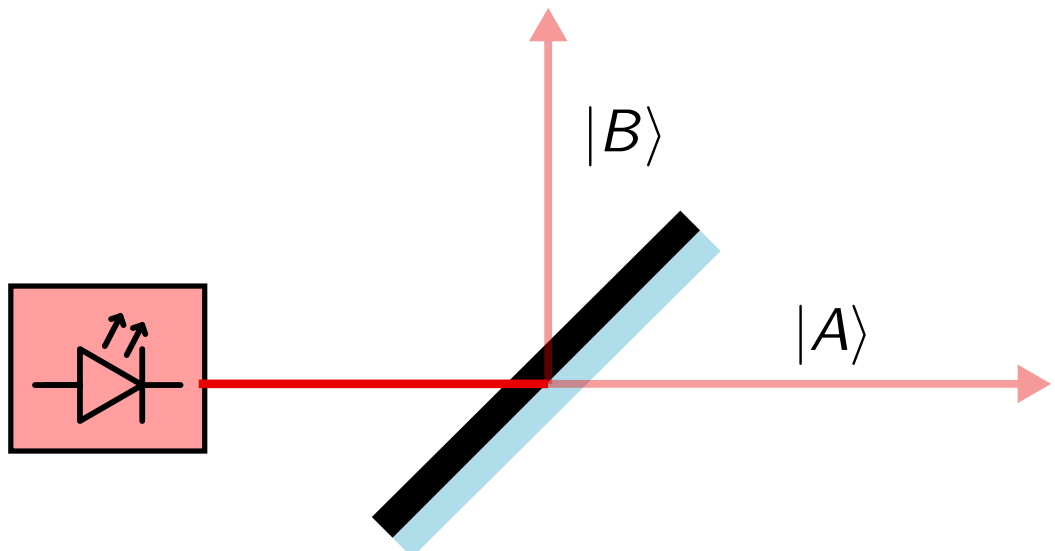

Copenhagen interpretation

- Evolution and observation are two different quantum phenomena
- Heisenberg: sharp 'cut' between the observer and the quantum system being observed
- Bohr: collapse involves irreversible, time-asymmetric processes

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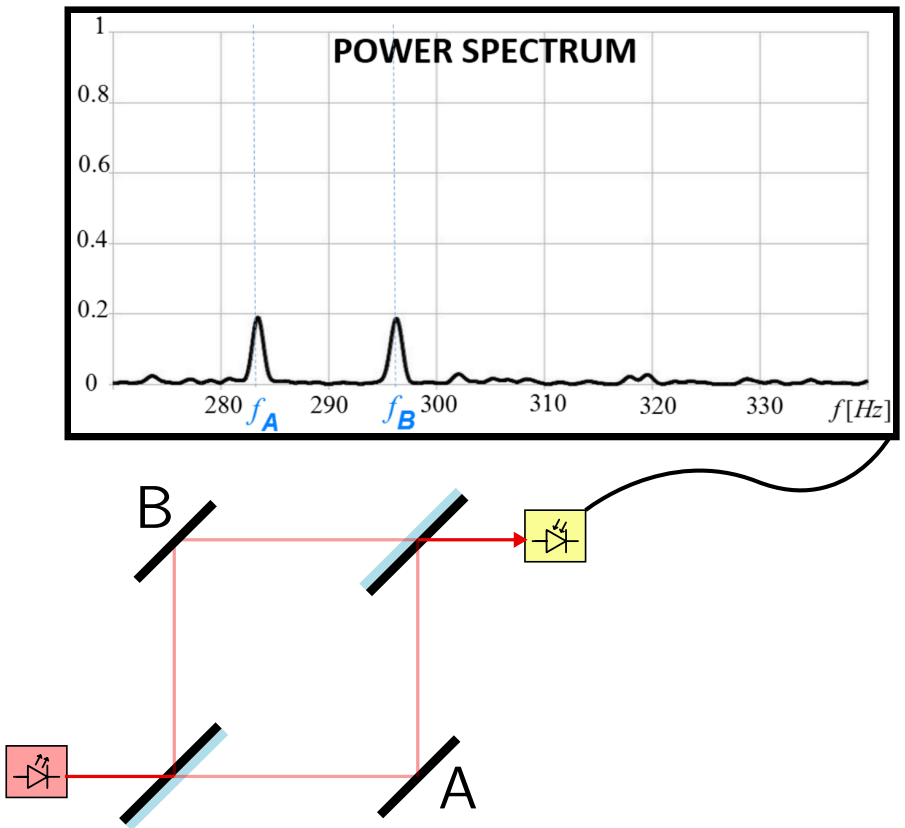
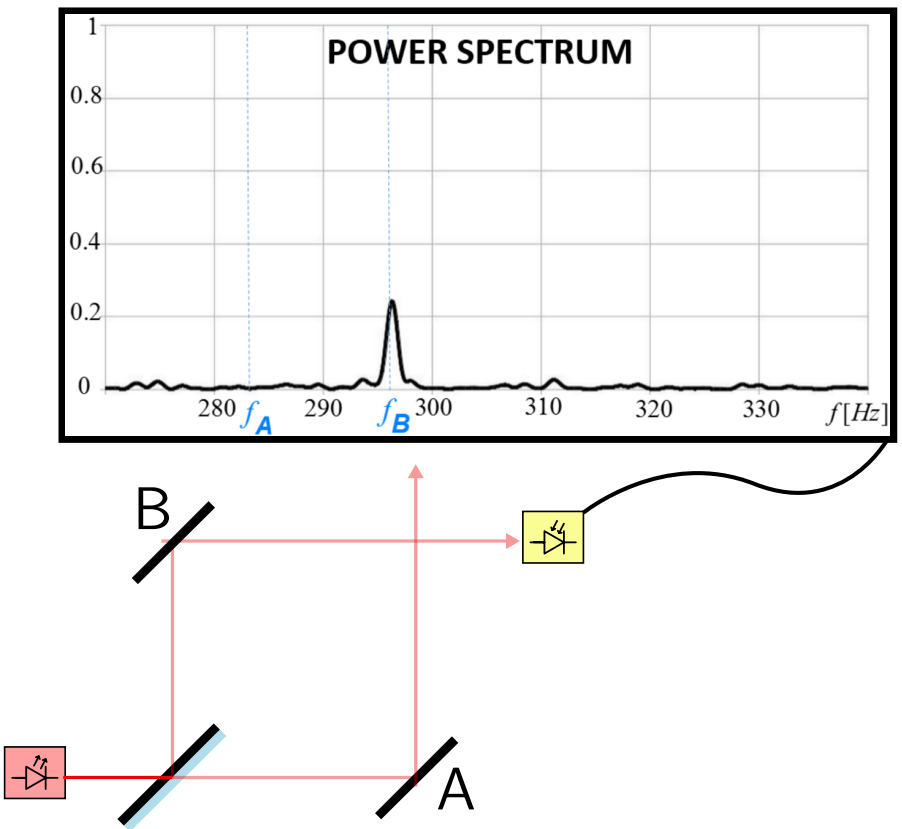
An enhanced MZ interferometer

- Published by Danan et al. in 2013
- Mirrors vibrating in vertical direction
- Low frequencies to prevent disruption in interference
- Confirms original experiment



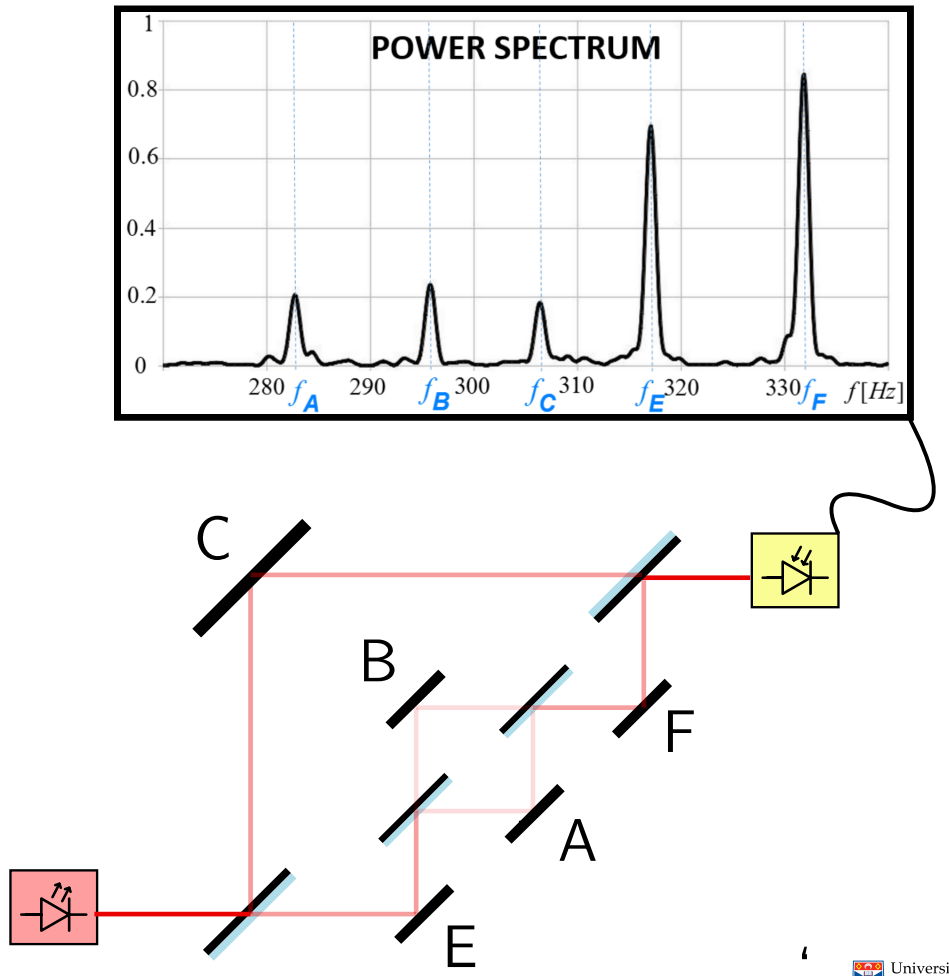
An enhanced MZ interferometer

- Second beam splitter was removed
- Only f_B shows up on graph, as expected



Nested Mach-Zehnder interferometer

- Initial beam splitter
  - $\frac{2}{3}$: transmitted ray, goes through mini MZ interferometer
  - $\frac{1}{3}$: reflected ray, reflected again towards detector
- As expected, all frequencies show up on spectrum



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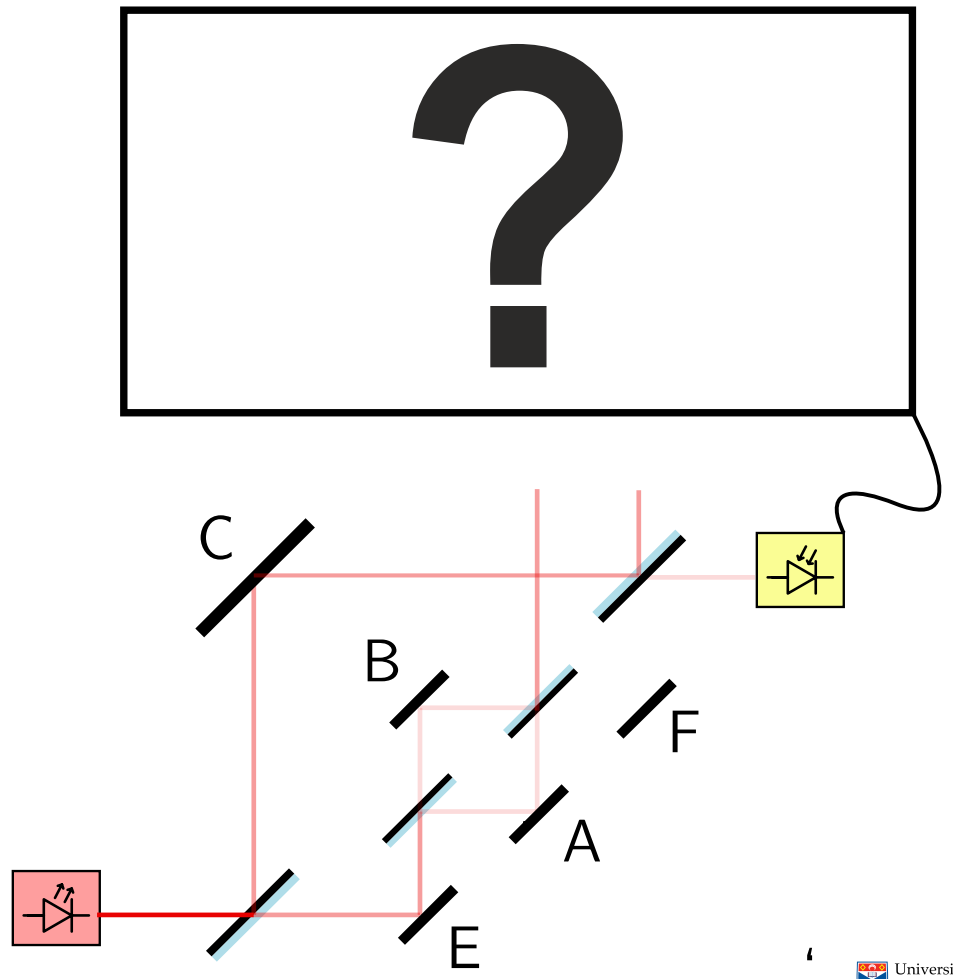
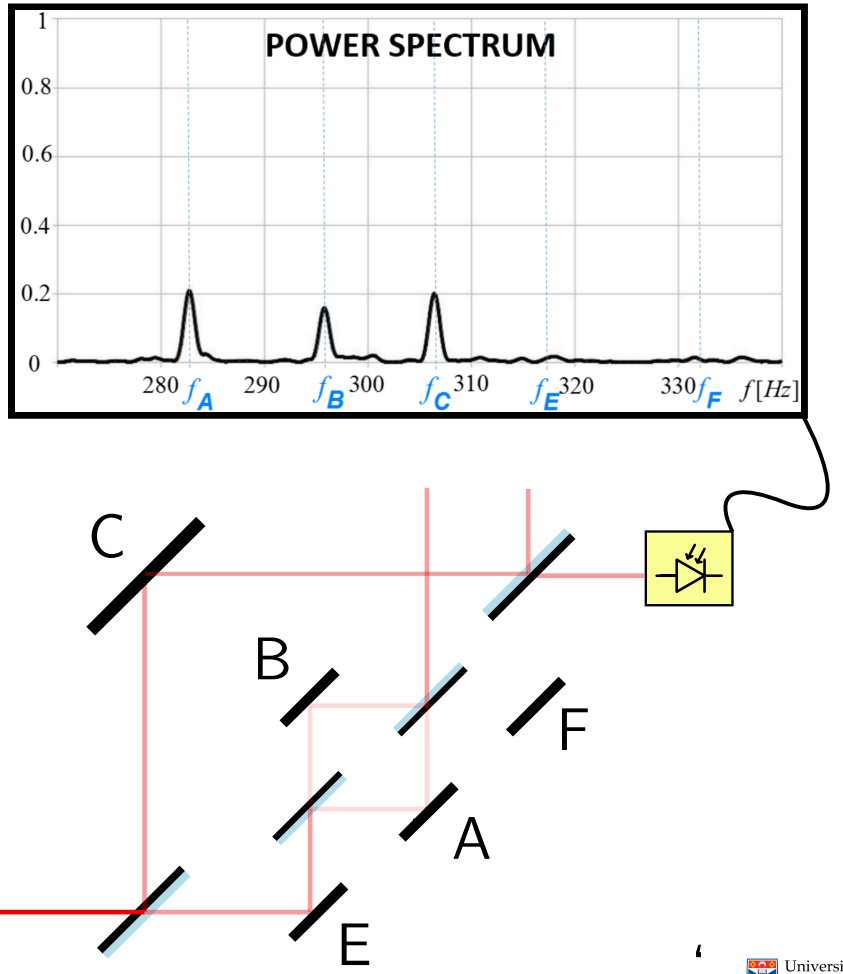
Nested Mach-Zehnder interferometer

- In the next step of the experiment, the second beam splitter is flipped



Some surprising results

- In the next step of the experiment, the second beam splitter is flipped
- Somehow, the frequencies of A and B show up on the spectrum even though the light rays passing A and B don't reach the photodetector



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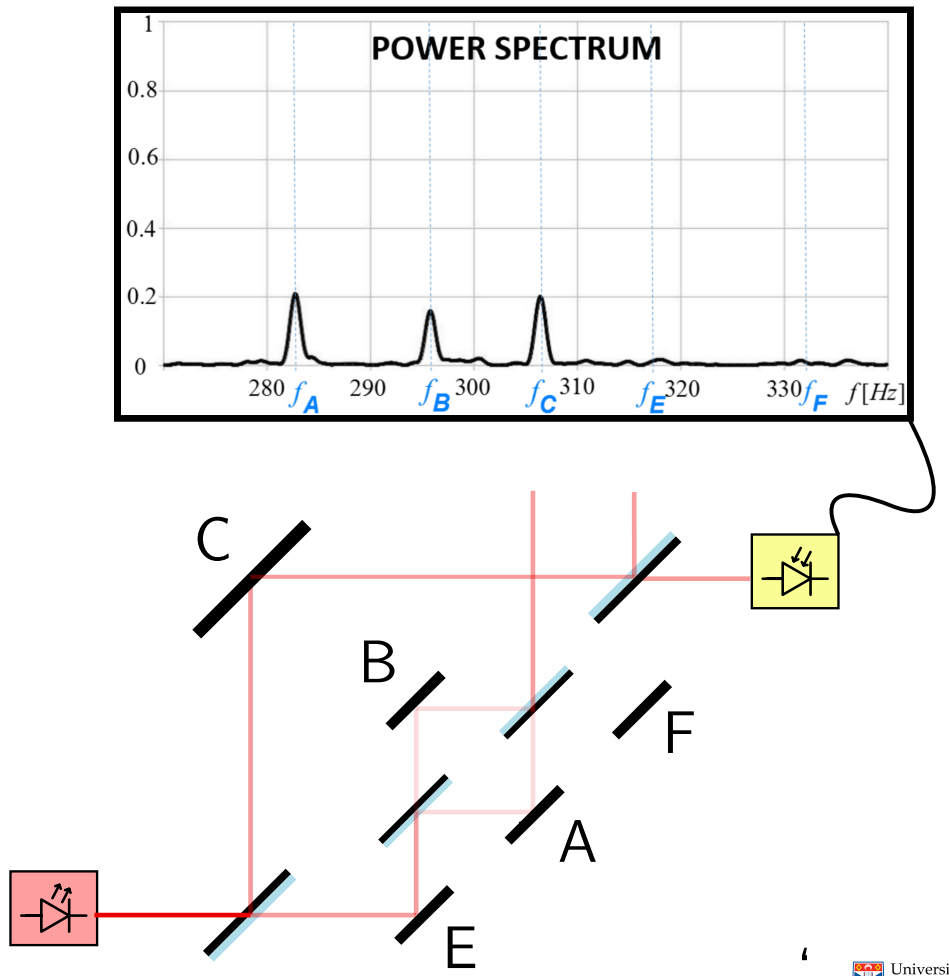

Some surprising results

Some questions arise:

- Q: How can photons from B show up on the detector if the only light reaching the detector is from C?
- Q: Why doesn't f_E show up on the graph?

A: Because the wavefunction of the photon evolving backwards from the detector interferes with itself!

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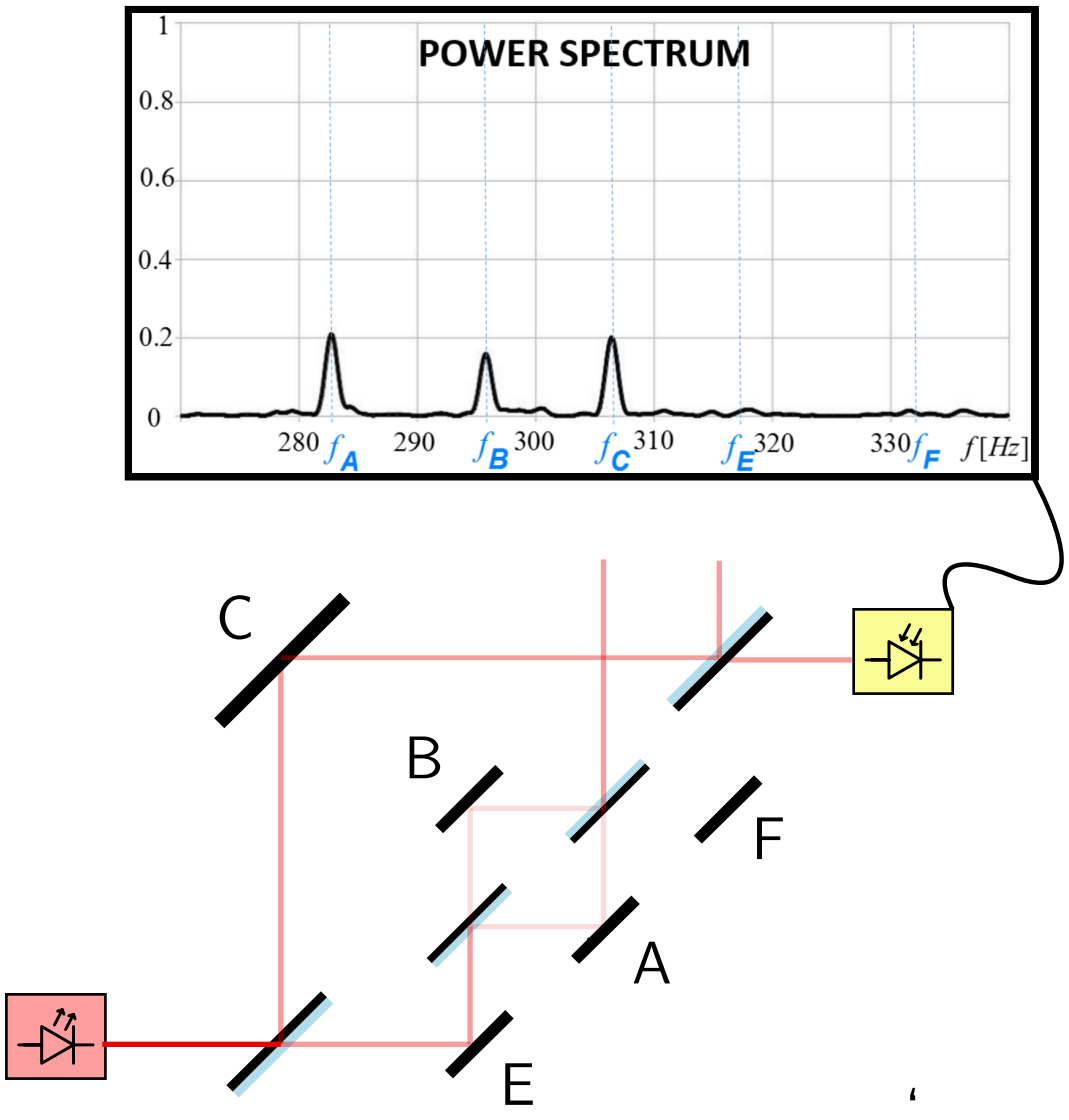

Two-state vector formalism

- Information about a particle at a point in time is provided together by two wave functions:
  1. The forward-evolving wave function originating from the light source
  2. The backward-evolving wave function "originating" from the detector
- This means that f_B shows up on the power spectrum because if you trace from the detector, a possible trajectory includes B

Two-state vector formalism

- Yields the same predictions as Standard quantum mechanics theories, but is easier to understand
- Experimental results defy "common sense" analysis frequently adopted. TSVF is intuitive and also accurate
- This formalism does not agree exactly with the Copenhagen interpretation

Summary

- The modified Mach-Zehnder interferometer is an accessible tool for performing which-way experiments and to probe the laws of quantum mechanics
- Danan et al.'s experiment yields counter-intuitive results that standard QM explains but are hard to understand
- An alternative is provided by two-state vector formalism of QM, which is easier to intuit and encodes time-reversibility of quantum phenomena

- Food for thought
  - How does TSVF complement the alternative interpretations?
  - Hhow does TSVF describe other fundamental quantum phenomena?

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For Further Reading I

A. Danan, D. Farfurnik, S. Bar-Ad, and L. Vaidman
Asking Photons Where They Have Been
Physical Review Letters 111, 240402 - Published 9 December 2013.

Y. Aharonov and L. Vaidman
The Two-State Vector Formalism: An Updated Review
Time in Quantum Mechanics 2, 399-447, 2008.